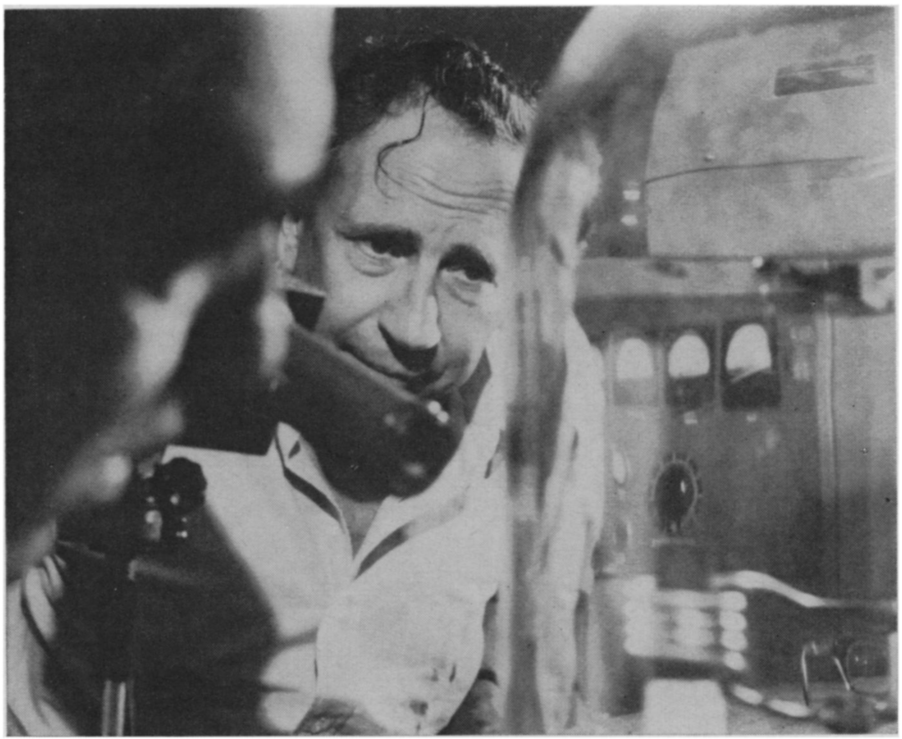
SOLID STATE PHYSICS

Search for a theory

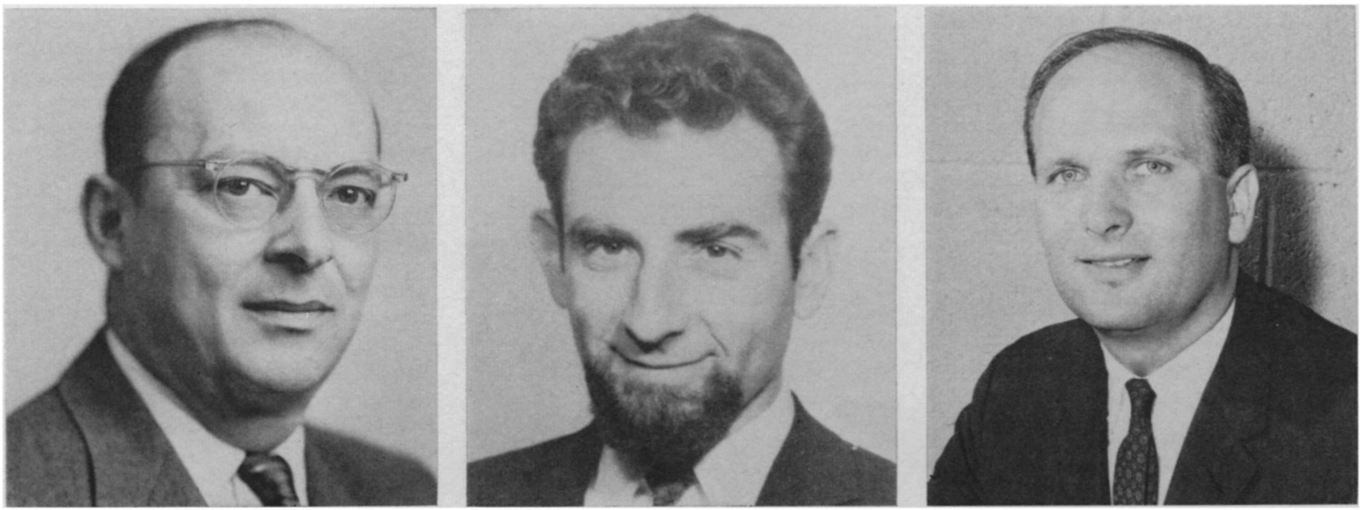
The phonon theory of superconductivity has only limited application

by Dietrick E. Thomsen



Bell Labs

Matthias: Pessimistic prospect for high temperature superconductivity.



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Drs. Bardeen, Cooper and Schieffer: Their theory provided a hope of superconductivity at high temperatures.

Superconductivity is the ability of certain materials to pass electric currents without resistance.

This phenomenon can be of great technological use since it would save large amounts of power in many applications. The rub is that it occurs only at temperatures very near absolute zero, a difficult state to achieve.

Each material that becomes a superconductor has a characteristic transition temperature at which it changes from an ordinary, or even a poor, conductor to a superconductor. Most known transition temperatures are within 20 degrees of absolute zero.

Scientists have long searched for materials that would become superconducting at higher temperatures. The current theoretical description of superconductivity fostered the hope that in principle there was no upper limit to the temperatures at which superconductivity might appear. A properly structured material—possibly organic—could even become superconducting at room temperature.

But years of testing material after material have succeeded only in raising the maximum transition temperature for conductivity from the four degrees K., at which the phenomenon was discovered, to 18 degrees K. Most recently it has gone to slightly more than 20 degrees K. In addition there is evidence that the relation between a metal's isotopic mass and its superconducting critical temperature, a ratio that led to the current theory, does not hold in all cases.

After musing on the frustration for some time, one of those who has spent years searching for higher and higher transition temperatures, Dr. Berndt T. Matthias of the University of California at San Diego and Bell Telephone Laboratories, now sounds a flatly pessimistic note.

The theory that has been applied so far, he says, is good for only a limited class of materials whose superconducting temperatures are by nature low. It cannot be used for the materials in which it would have predicted higher

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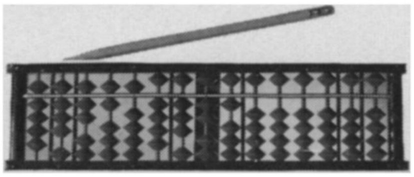

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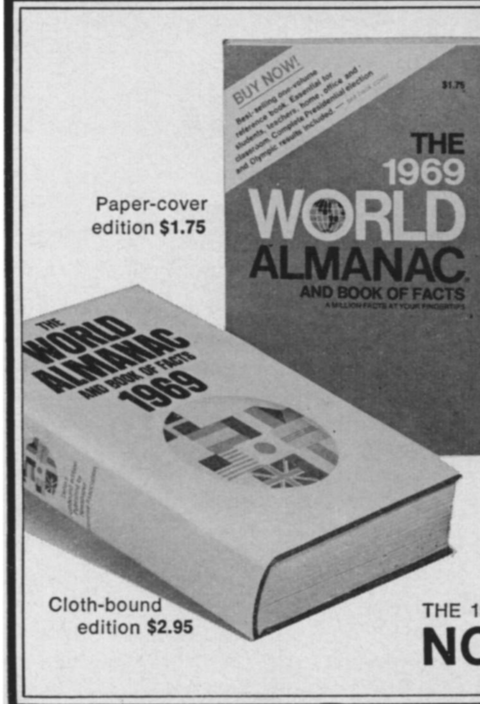

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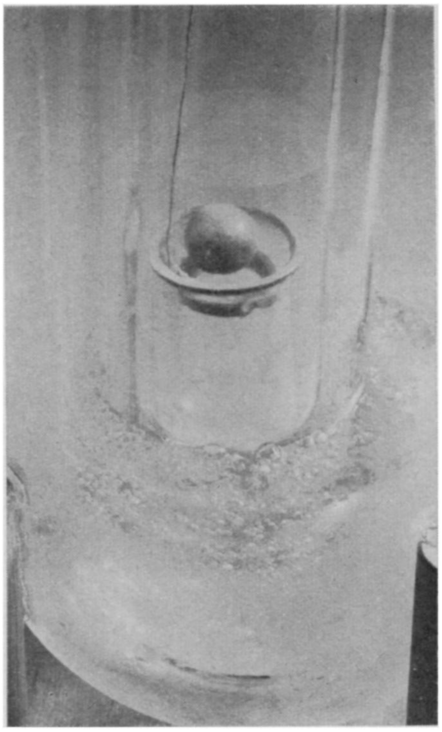

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Supercurrents suspend a lead ball.

critical temperatures. A new theory has to be evolved for those materials, and it may not be so promising, he says.

The present theory was put forward in 1957 by Drs. John Bardeen, Leon N. Cooper and J. R. Schrieffer. It seeks to explain superconductivity on the basis of relations between free electrons in a metal and vibrations of the metal's crystal lattice. These vibrations can be treated mathematically as if they were particles called phonons, moving through the bulk of the metal, much as electromagnetic vibrations are treated as particles called photons.

The phonons' function in the theory is to mediate between electrons, which, if left to themselves, tend to repel each other. Interposition of a phonon of the proper frequency can change the balance of forces so that there is a net attraction between two electrons. This attraction binds the electrons in pairs, and when the pairs consist of electrons with opposite momentums and spins, the energy and momentum characteristics of the material are changed so that persistent, unresisted electric currents can flow in it.

The success of the theory as an explanation—and experimental confirmation that the electron-phonon interaction did in fact occur—led to a rush of speculation and experiment. "There were 1,000 papers," says Dr. Matthias, "predicting temperatures from 40 degrees to 1,000 degrees. Five thousand pages by 500 investigators, and what was the result? There was none. With the possible exception of magnetic monopoles, this is the most fruitless endeavor I have seen."

The basis of all this speculation is wrong, he says. "The electron-phonon interaction is all right for non-transition elements," those whose atoms lack incomplete inner electron shells. The maximum critical temperature for these is nine degrees, in a lead-bismuth alloy. "There is no way to get higher," says Dr. Matthias. "People have tried just about every way." Dr. Matthias does see hope, however, of higher temperatures in transition elements, those that have incomplete inner electron shells. But here, he says, "the BCS (Bardeen-Cooper-Schrieffer) theory does not work."

Dr. Bardeen concedes that the phonon picture may be limited to low temperatures, but insists that the overall theory is still valid. "It depends on what you mean by BCS theory," he says. "The general theory applies to any attraction between electrons. If it comes through phonons, the transition temperature is limited to not over 20 degrees. If you want to go substantially above that, you have to find some other mechanism."

Dr. V. L. Ginzburg of the P. N. Lebedev Physical Institute in Moscow has an idea of what kind of a mechanism that might be. "It is quite possible," he says, "that a non-phonon mechanism of superconductivity plays a noticeable part in some superconducting metals and alloys (especially transition metals), but it is not easy to elucidate it."

He suggests that a more general class of excitations than phonons, the so-called excitons, may be responsible. Excitons include various kinds of undulating disturbances of the electrons themselves, acoustic or plasma waves for instance, as well as including phonons as a particular case.

Excitons could contribute particularly to superconductivity in one- and two-dimensional systems: long chain molecules, layers and sandwiches. One-dimensional superconductivity was proposed in 1964 by Dr. W. A. Little of Stanford University, and since many organic substances come in long chain molecules, there was speculation that some organic systems might be superconducting at room temperature. Nothing of the sort has ever been found experimentally, however.

Dr. Ginzburg proposes a kind of sandwich in which excitons moving in outer layers of insulating material would cause superconductivity in the surface of a middle, metal layer.

Many theories in this branch of physics are approximate because the physical qualities on which they are based are poorly known for many substances. Dr. Matthias and others have recently gone so far as to complain that "there is no theory whatsoever for high transition temperatures."

In response to this Dr. W. L. McMillan of Bell Telephone Laboratories, a former student of Prof. Bardeen, has worked out a theory on the basis of the electron-phonon interaction, whereby he can calculate a maximum critical temperature for a group of similar materials if he knows the critical temperature and certain structure characteristics for one of them.

On this basis, Dr. McMillan says, "the theoretical maximum transition temperature for lead-like materials is 9.2 degrees K., and there is in fact a lead-bismuth alloy with transition temperature equal to 8.8 degrees K."

Critical temperatures predicted by Dr. McMillan's system, but not yet observed, go as high as 40 degrees K.

Dr. Matthias' hope for higher critical temperatures goes in a different theoretical direction. "Transition elements and their compounds will give high critical temperatures," he declares. He makes some tentative steps in the direction of a new mechanism. The material, he says, has to be a three-dimensional array, it has to be a metal; and it has to be a cubic crystal. "All above 10 degrees are cubic," he says. These conditions mean there can be no linear chains, no organic molecules, and no surface superconductors. "I admit it's a depressing thought," he says.

Another quality that seems closely related to superconducting temperature in these transition metal materials is the melting point. In general, says Dr. Matthias, the lower the melting point the higher the critical temperature.

He suggests that the reason the melting point and critical temperature are related is that in transition elements all electrons outside filled shells, and not merely the loose conduction electrons, take part in superconductivity, and it is these electrons that also determine the melting point.

In this case pressure can also enter the picture since it will alter electron configurations. Platinum, for instance, is a superconductor at six degrees, says Dr. Matthias, but if it is squeezed to 160,000 times atmospheric pressure, the critical temperature goes to 30 degrees, and that is at least as troublesome as cryogenic temperatures.

"Sad to say," says Dr. Matthias, "we are referring a phenomenon (superconductivity) which we do not understand to a phenomenon (theory of melting points) we understand even less." ◇